Searching for Light Dark Matter from Accelerator-driven Neutrino Programs

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on behalf of the authors of
SNOWMASS21-NF3 NF0-RF6 RF0-CF1 CF3-TF9 TF11-148
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Overview

1) Introduction
2) Signal and Background
3) Experimental Landscape & Tools
4) Summary

Evidences of Dark Matter

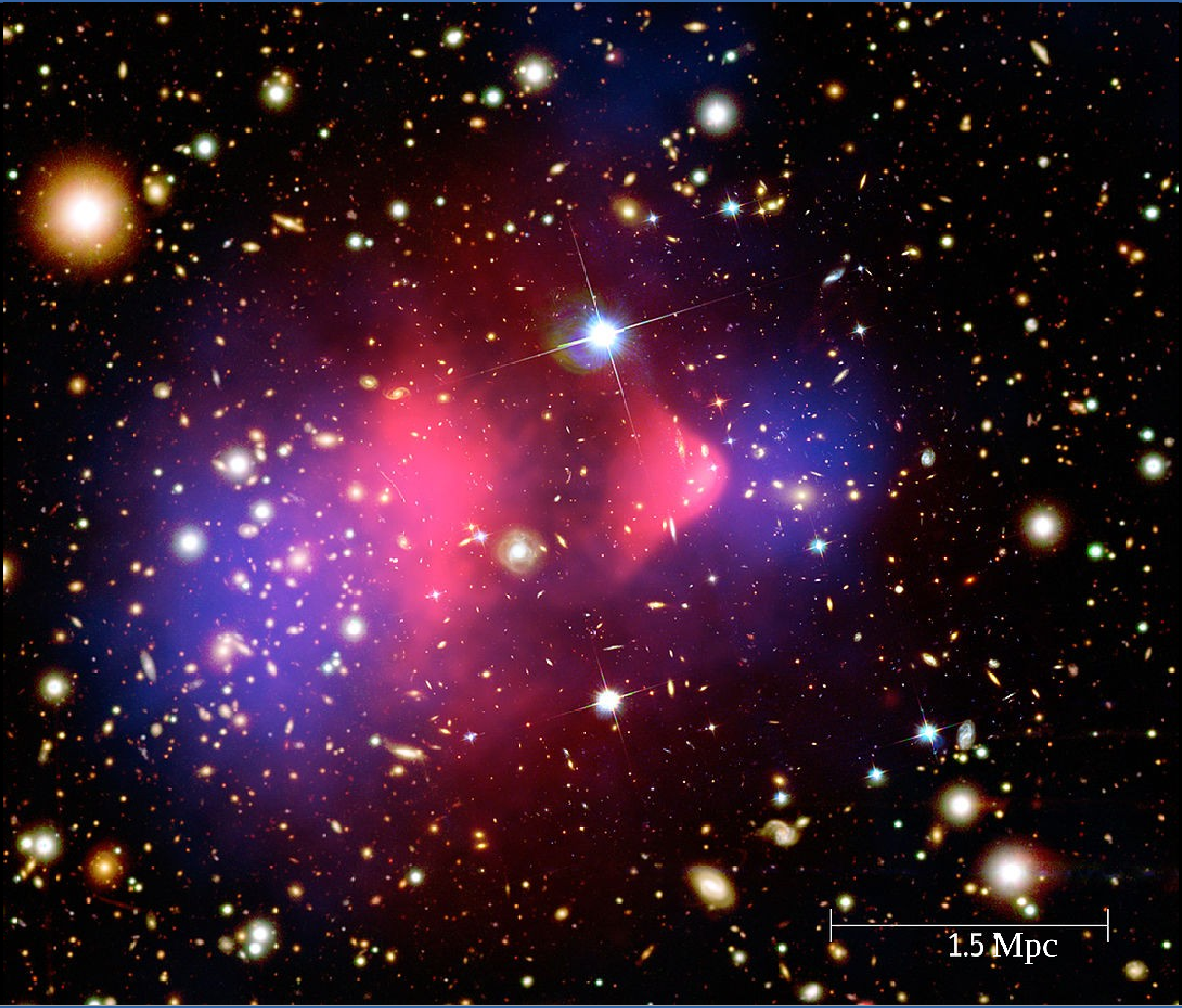

Fig. 1 - Bullet cluster, X-ray image(red) overlayed on a matter distribution (blue)

Evidences of Dark Matter (cont'd)

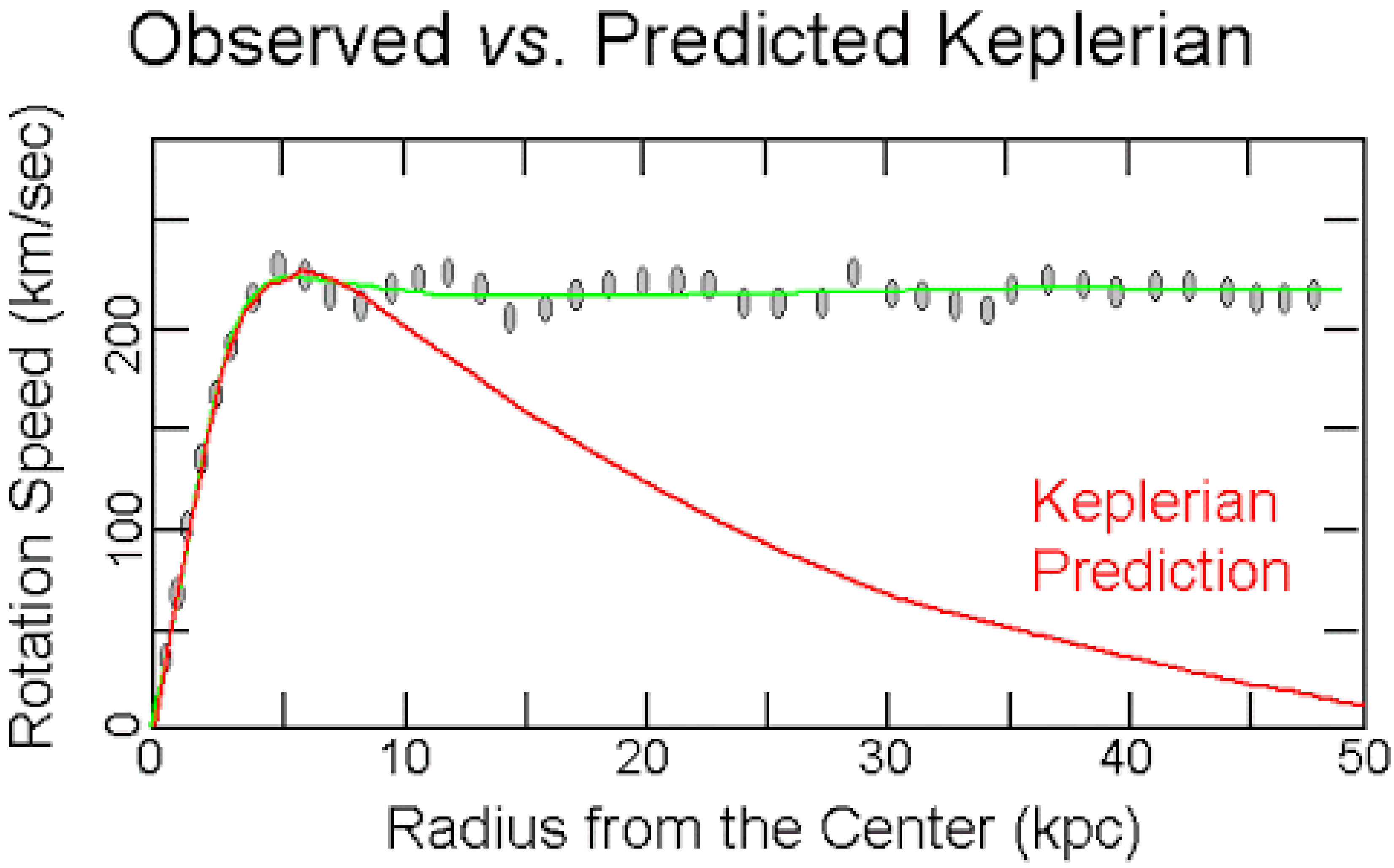

Fig. 2 – A typical galaxy rotation curve
(http://astronomy.ohio-state.edu/~thompson, pogge.1@osu.edu)

Weakly Interacting Massive Particle

- 1977, Steven Weinberg and Benjamin W. Lee calculated the lower limit of mass of possible stable neutral **heavy** leptons. → WIMP

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Cosmological Lower Bound on Heavy-Neutrino Masses

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and

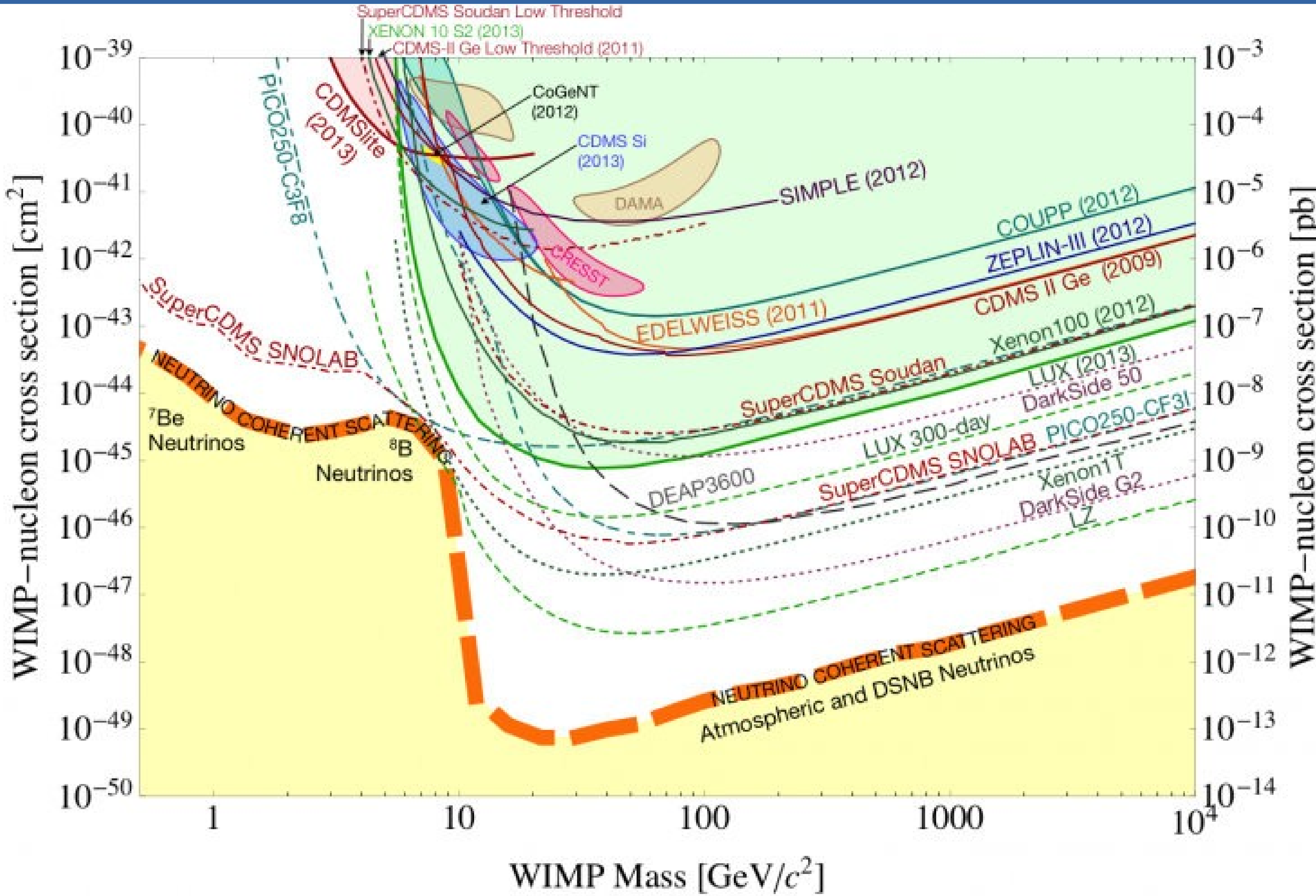
Steven Weinberg[(c)]

Stanford University, Physics Department, Stanford, California 94305

(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

Searching for WIMP by Direct Detection

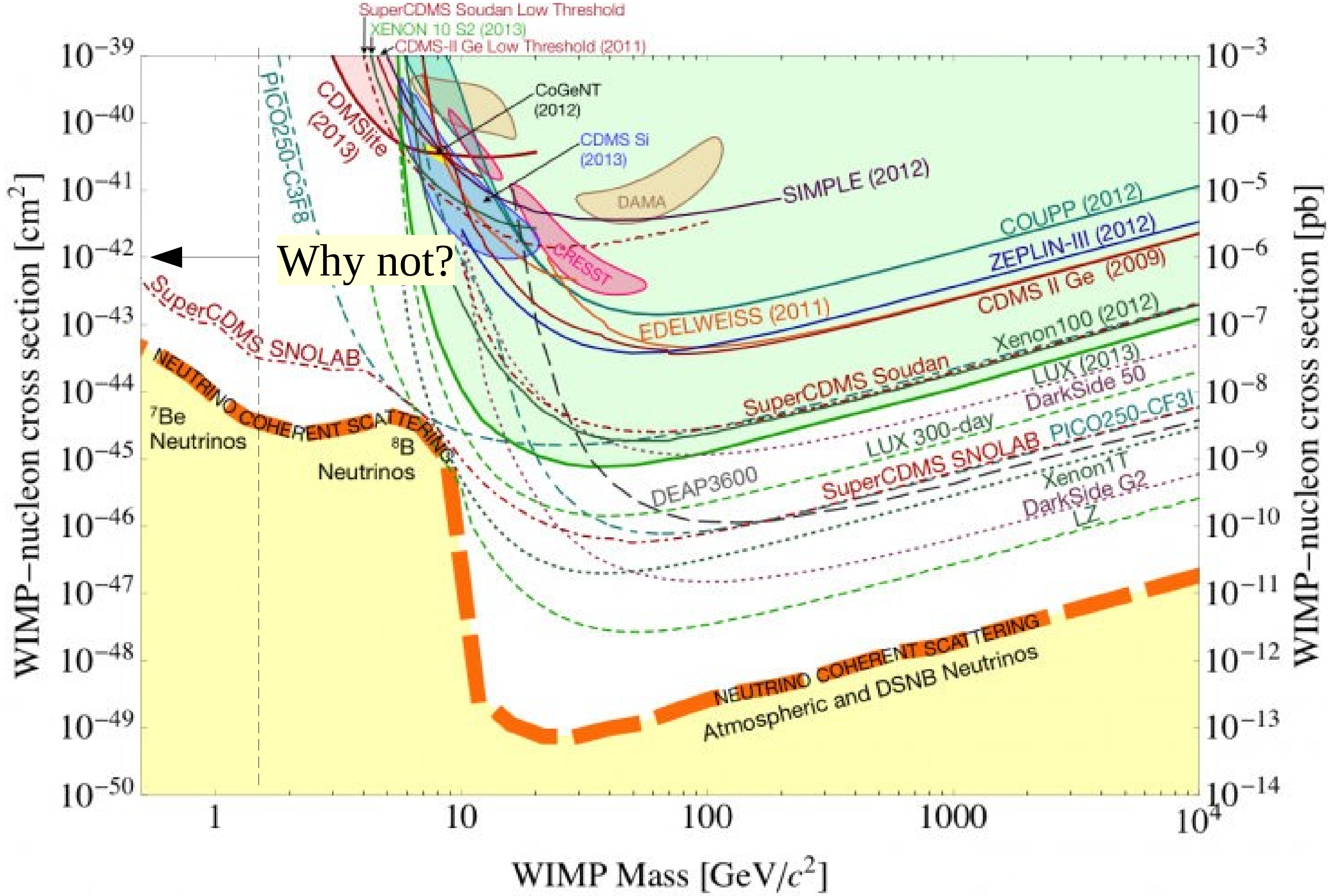


Looking into Another Frontier

- Still, many of physicists keep searching for traditional WIMP and we have to keep continue this. But some of those physicists, naturally, trying to look into the other frontier.

- In this new frontier, still, dark matter must interact very weakly with SM particles.

- In a perspective of SM, sub-GeV dark matter is known as forbidden by Lee-Weinberg Limit.



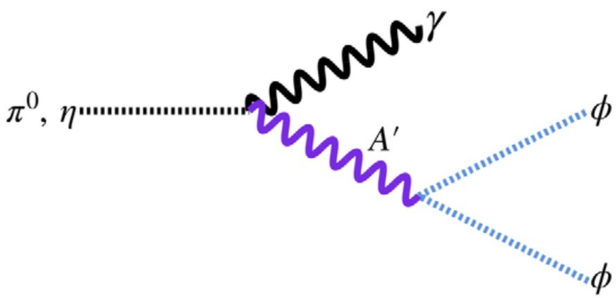
Portal Interactions

- However, if we introduce a new interaction called *portal* interaction, we can think about new DM models in sub-GeV mass scale. Below is a summary of many dark sector particle (DSP) models.

Model	Production	Detection
Higgs Portal	K, B decay	Decay ($\ell^+\ell^-$)
Vector Portal	π^0, η Decay Proton Bremmstrahlung Drell-Yan	Scattering (χe^-, χX, Dark Tridents) Decay ($\ell^+\ell^-$, $\pi^+\pi^-$) Inelastic Decay ($\chi \to \chi'\ell^+\ell^-$)
Neutrino Portal	π, K, $D_{(s)}$, B decay	Decay (many final states)
ALP Portal (γ-coupling dominant)	Meson Decay Photon Fusion Primakoff Process	Decay ($\gamma\gamma$) Inverse Primakoff process
Dark Neutrinos Dipole Portal	SM Neutrino Dalitz Decay	Upscattering + Decay ($\nu \to \nu_D$, $\nu_D \to \nu\ell^+\ell^-$) Decay ($\nu_D \to \nu\gamma$)
νphilic Mediators	SM Neutrino	Scattering (Missing $\not{p}_T$, SM Tridents)

- In this LOI, we are focusing on the vector portal interaction and it leads us to the Light Dark Matter (LDM) search.

Light Dark Matter (Signal)

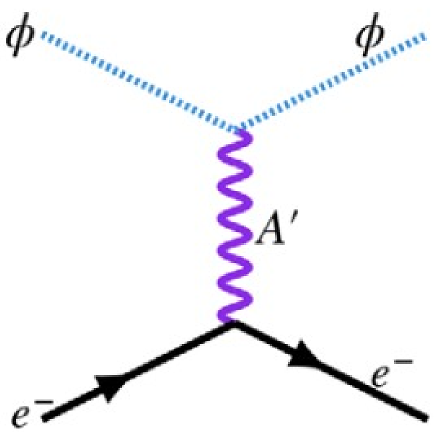


- In this model, the new vector boson (*A'*) is coupled with SM photon and produce a DM(*φ)* pair from decays of **neutral mesons,** such as π^0 or η.
- So, in order to produce those neutral mesons, **high-intensity accelerator beam** is necessary.

We produce DM beam!

– Detection: $\varphi + e^- \rightarrow \varphi + e^-$ **or**

$\varphi + N \rightarrow \varphi + N$



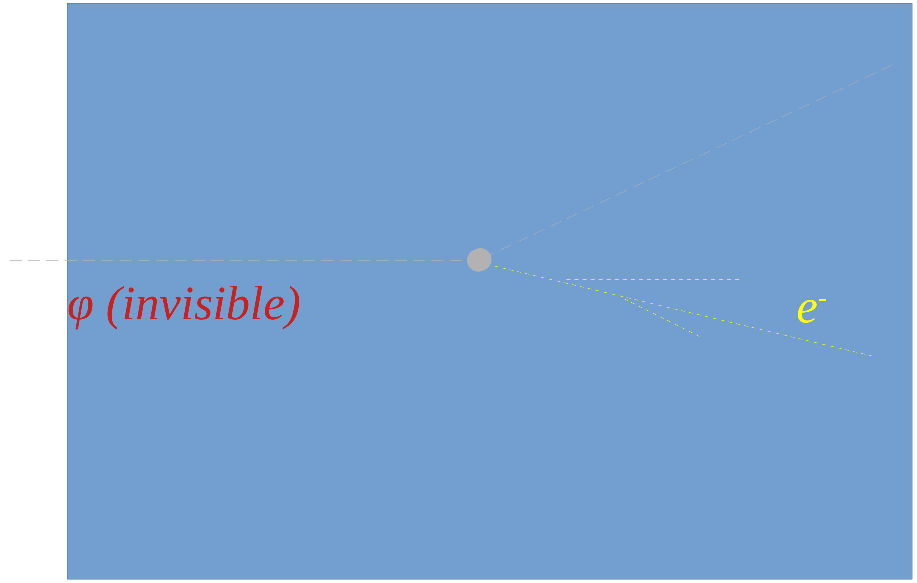
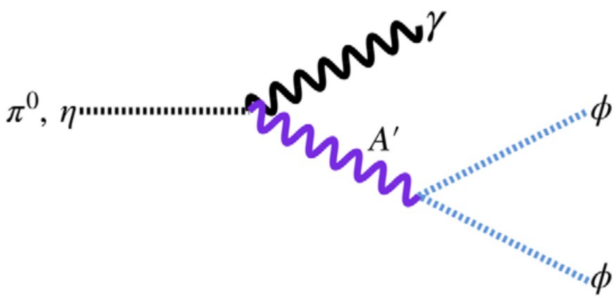


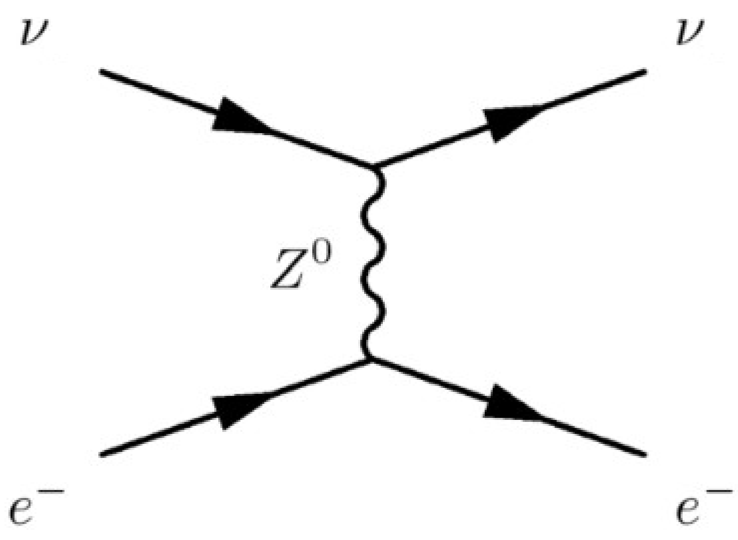
Figure from [10.1103/PhysRevD.100.095010]

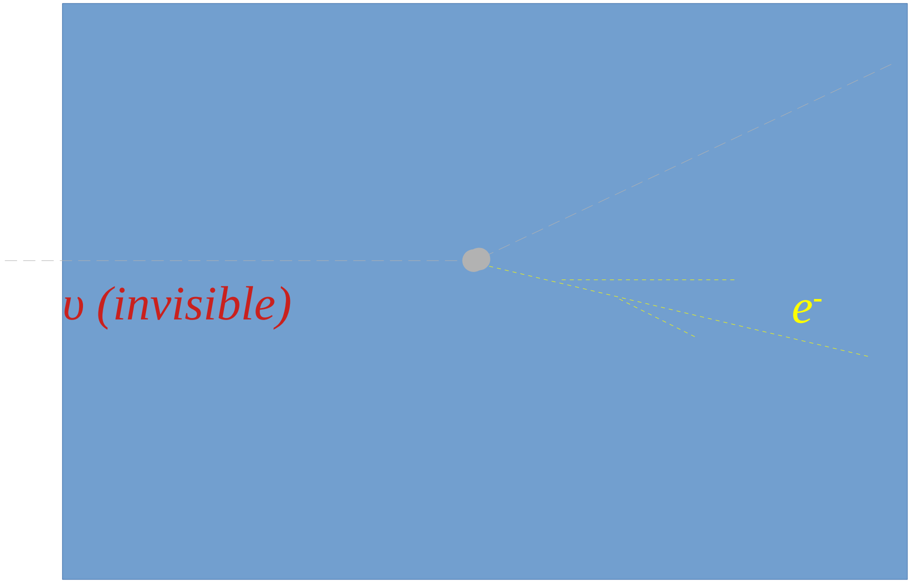
Light Dark Matter (Background)



- In this model, the new vector boson (*A'*) is coupled with SM photon and the produce a DM(*φ)* pair from decays of **neutral mesons,** such as π^0 or *η*.
- So, in order to produce those neutral mesons, high intensity accelerator beam is necessary.

– Background: ***ν + e⁻ → ν + e⁻***

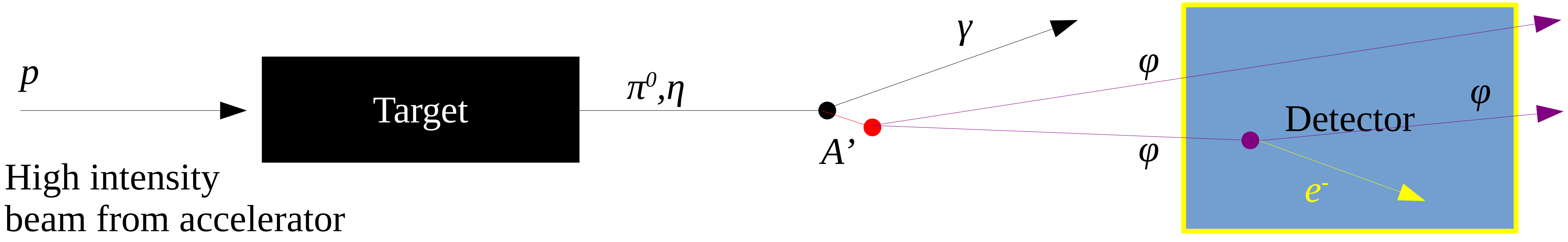




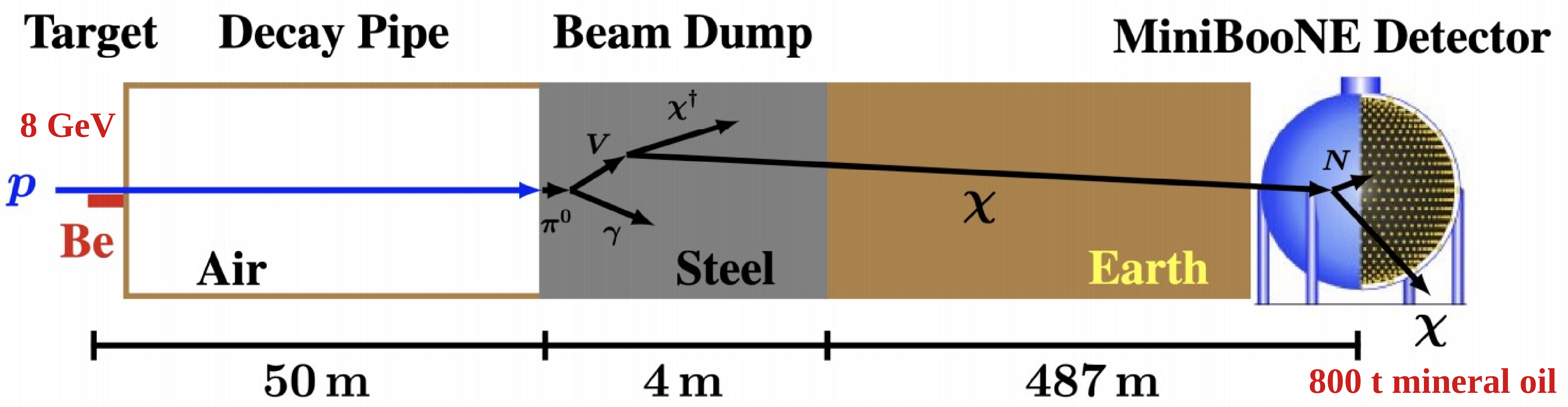
and subdominant channels: υ_e+Ar → e^- + X
υ+Ar → υ+Ar+π^0

Why Neutrino Facilities? - Experimental Landscape

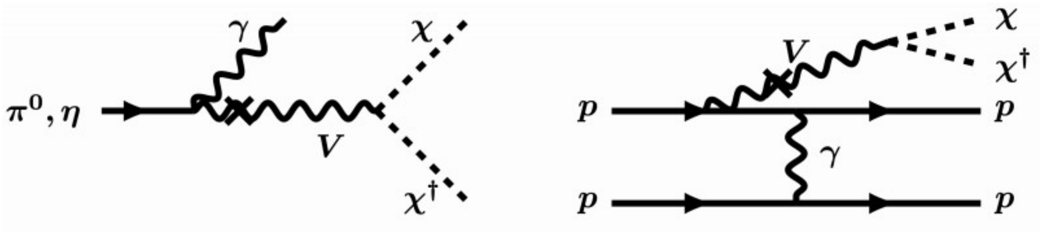
- Based on those signal and background characteristics, there are two experimental requirements:
  - **High-intensity proton beam** - More neutral meson production, more proton bremsstrahlung.
  - **Detectors with precision, accuracy and sensitivity** – Better efficiency and S/N ratio.
- There are many experiments meet those requirements. In many cases they're capable to search for other dark sector models simultaneously.
  - CHARM, Nu-Cal, MINOS, MiniBooNE(-DM), MINERvA, T2K, MicroBooNE, ICARUS, SBND, T2HK, DUNE and more...



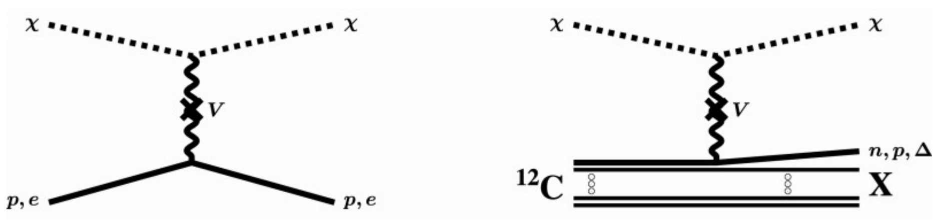
Light Dark Matter at MiniBooNE



- In 2013/2014, MiniBooNE operated a dedicated beam dump run. [1807.06137]
- Neutral pion decay / proton bremsstrahlung can produce DM and DM travel to MiniBooNE.
- Beam dump suppresses neutrino “background”, and it allows more sensitivity.

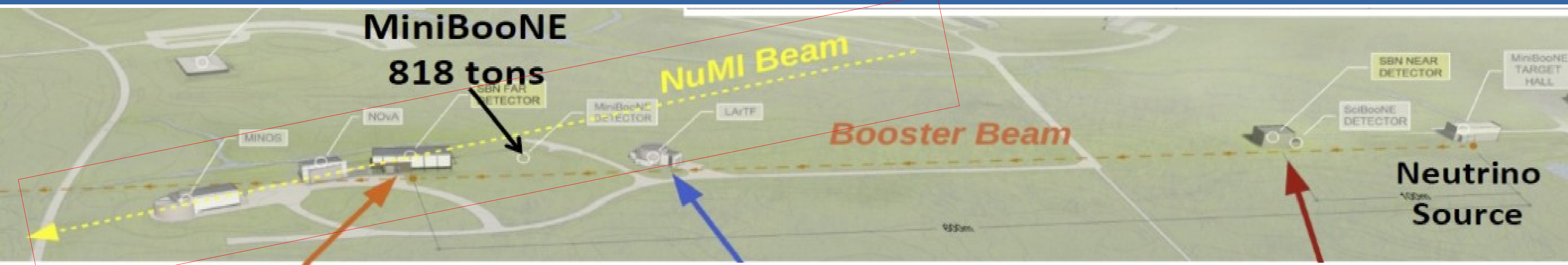


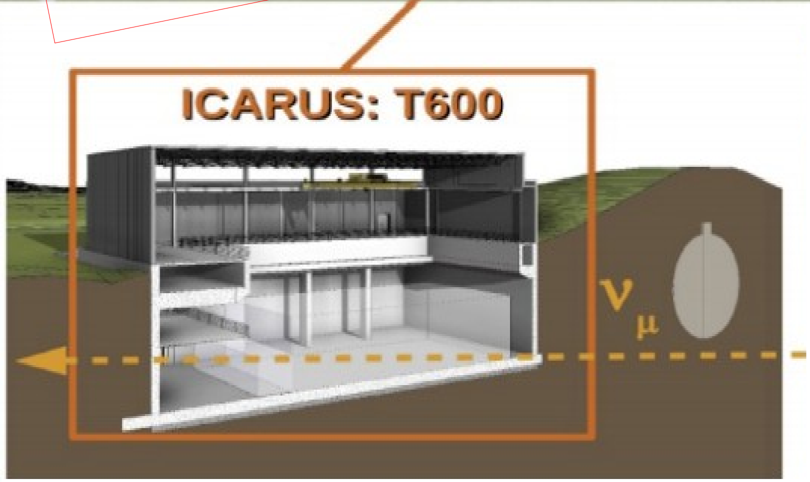
[DM Production]

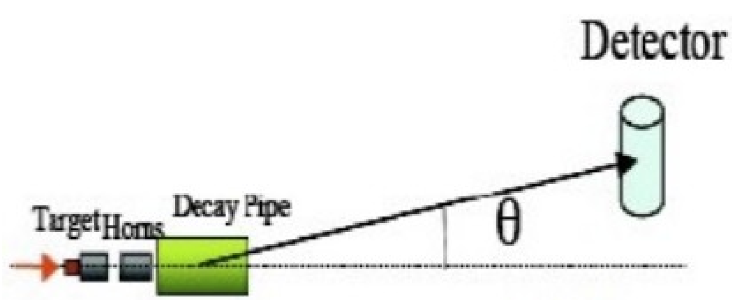


[DM Scattering]

Light Dark Matter at ICARUS NuMI Off-Axis





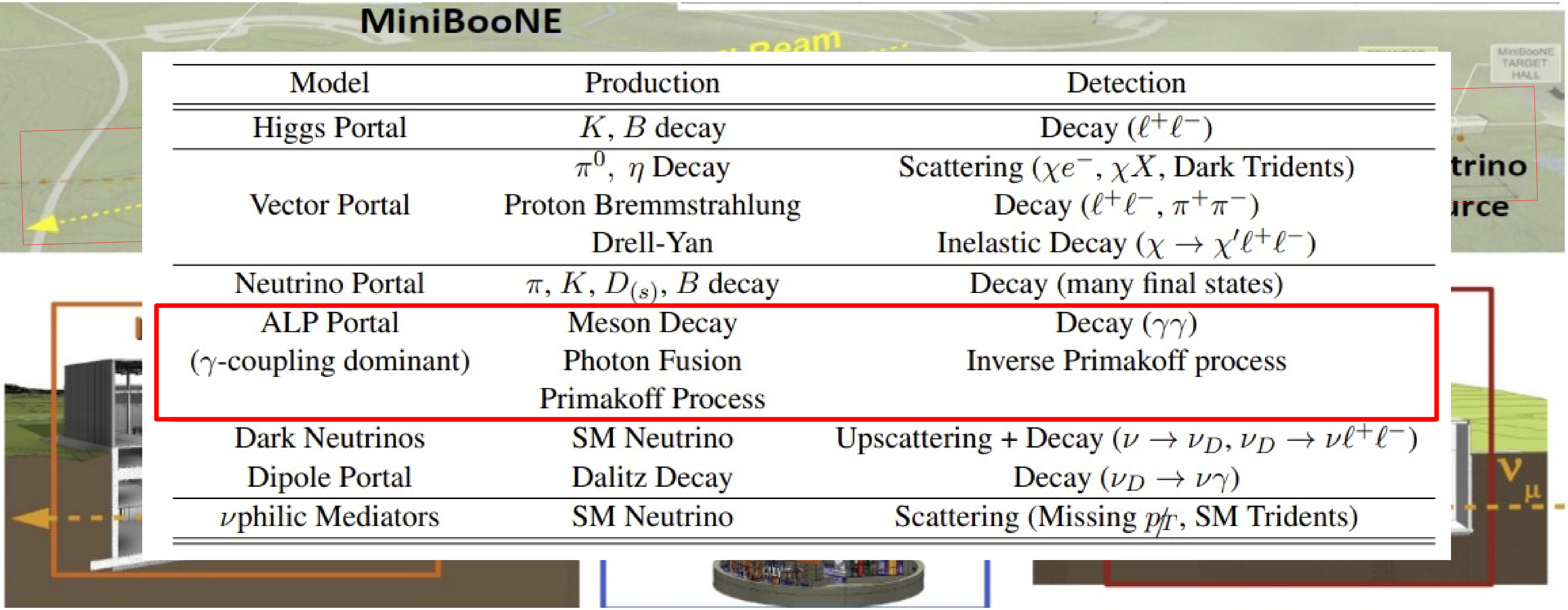


$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$

- The primary goal of the ICARUS experiment is the sterile neutrino search.
- However, since the ICARUS detector is located **~103 mrad off axis** from NuMI (Main Injector) beam, this reduces neutrino background a lot.
- Therefore, ICARUS detector with NuMI off axis beam will play a key role in BSM searches, including the LDM search.
- The detector commissioning ongoing, will start taking with neutrino beam in mid November of this year.

SNOWMASS21-NF3 NF0-RF6 RF0-CF1 CF0

Light Dark Matter at SBN Programs



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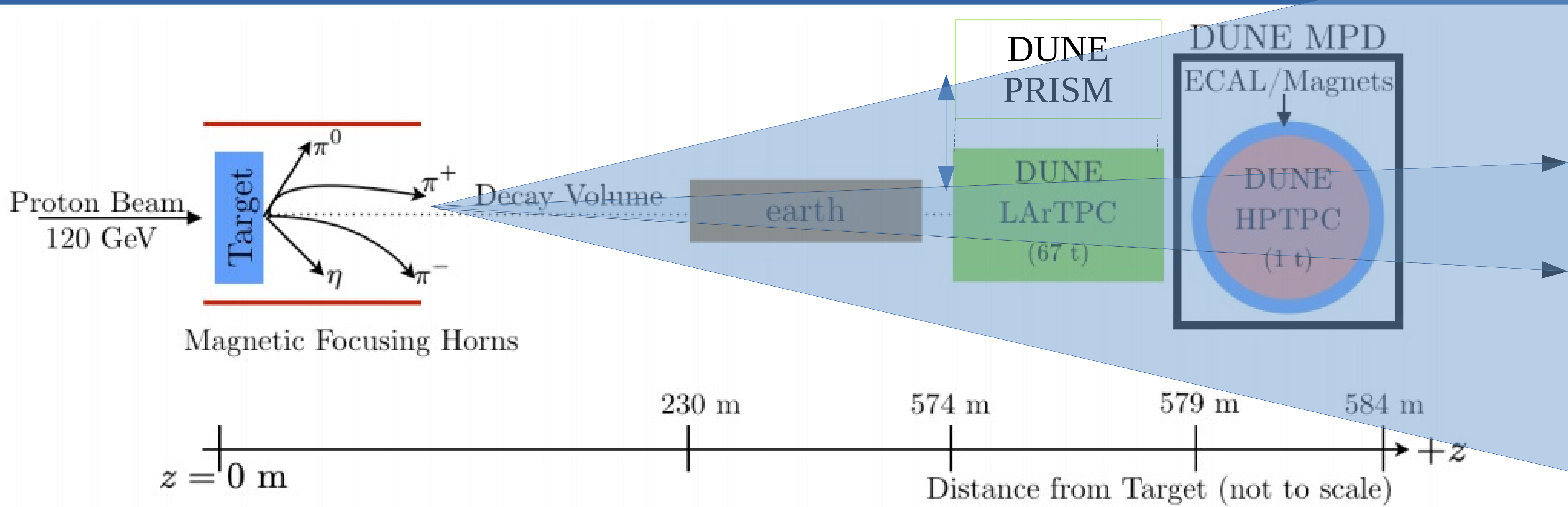
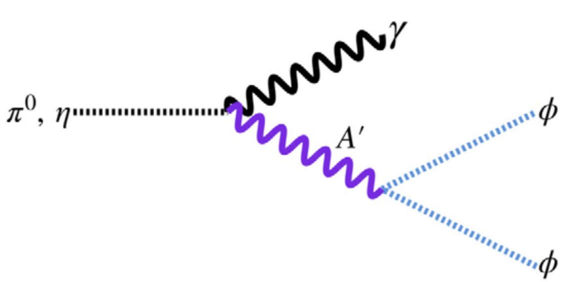
Dark Neutrinos	SM Neutrino	Upscattering + Decay ($\nu \to \nu_D$, $\nu_D \to \nu\ell^+\ell^-$)
Dipole Portal	Dalitz Decay	Decay ($\nu_D \to \nu\gamma$)
νphilic Mediators	SM Neutrino	Scattering (Missing $\not{p}_T$, SM Tridents)

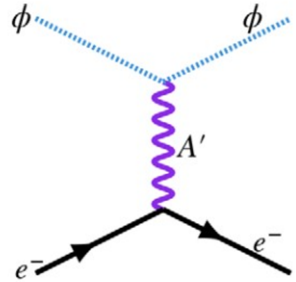
- The short baseline program can also contribute to the LDM search.
- Using the 8 GeV booster beam, we can investigate much lower mass region of light dark matter.
- In addition to this, potentially the SBND program can provide another interesting chance to explore the '**ALP portal**' of the dark sector using the LArTPC there.

Light Dark Matter at DUNE



- 120 GeV high intensity proton beam strikes graphite target layers.
- Neutral meson decay produces DM particles and DM travel to the DUNE ND.
- The Off-Axis concept called **DUNE-PRISM** can significantly reduce neutrino backgrounds.





MC Software/Tools

- New tools are being developed to study LDM.
  - DM Production : BdNMC, MG5aMC
  - Neutrino MC : GENIE
  - Tweaked Geant4 simulation using cross section biasing technique:

Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and SHiP

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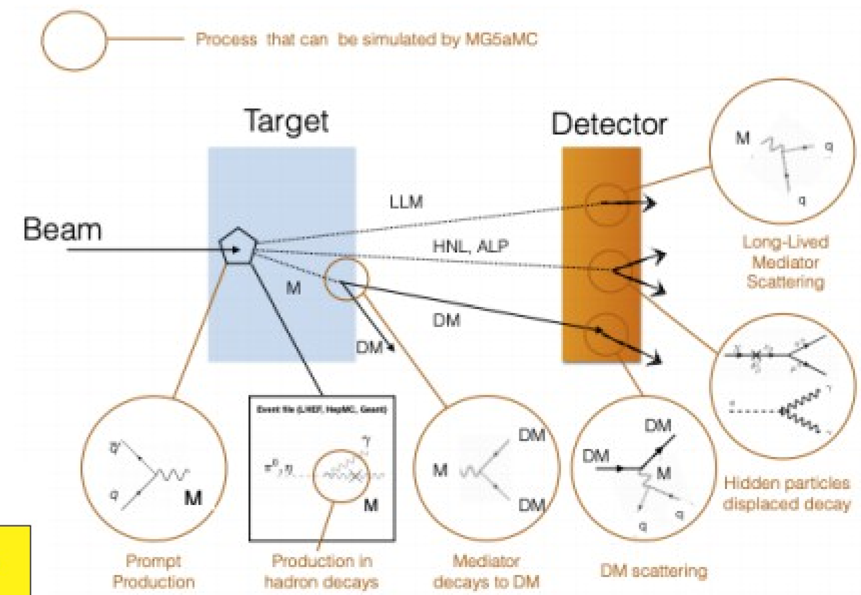
[1] *Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 5C2, Canada*
[2] *Perimeter Institute for Theoretical Physics, Waterloo, ON N2J 2W9, Canada*

(Dated: September 2016)



A Module For Boosted Dark Matter Event Generation in GENIE

Joshua Berger

Models that produce a flux of semi-relativistic or relativistic boosted dark matter at large neutrino detectors are well-motivated extensions beyond the minimal weakly interacting massive particle (WIMP) paradigm. Current and upcoming liquid argon time projection chamber (LArTPC) based detectors will have improved sensitivity to such models, but also require improved theoretical modeling to better understand their signals and optimize their analyses. I present the first full Monte Carlo tool for boosted dark matter interacting with nuclei in the energy regime accessible to LArTPC detectors, including the Deep Underground Neutrino Experiment (DUNE). The code uses the nuclear and strong physics modeling of the GENIE neutrino Monte Carlo event generator with particle physics modeling for dark matter. The code will be available in GENIE v3. In addition, I present a code for generating a GENIE-compatible flux of boosted dark matter coming from the Sun that is released independently.

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journal homepage: www.elsevier.com/locate/nima

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GEANT4 neutrino-electron interaction model

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Check for updates

Summary

- The nature of dark matter (DM) and the origin of neutrino masses remain among the most pressing puzzles in particle physics. We are trying to explore low mass region in the dark matter parameter space.
- A high-intensity accelerator beam can be regarded as dark matter beam(!) in some perspective. In this view, accelerator-driven neutrino experiments provide great advantages to BSM studies not only the LDM study but also many other dark sector studies.
- Neutrino experiments, both those currently operating and those slated to begin soon, will play a crucial complementary role in probing light dark matter.

Q & A